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Association of Residential Energy Efficiency Retrofits with Indoor Environmental Quality, Comfort, and Health: A Review of Empirical Data

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ABSTRACT

This paper reviews empirical data from evaluations of the influence of residential energy efficiency retrofits on indoor environmental quality conditions and self-reported thermal comfort and health. Data were extracted from 36 studies described in 44 papers plus two reports. Nearly all reviewed studies were performed in Europe or United States. Most studies evaluated retrofits of homes with low-income occupants. Indoor radon and formaldehyde concentrations tended to increase after retrofits that did not add whole-house mechanical ventilation. Study-average indoor concentrations of nitrogen dioxide and volatile organic compounds other than formaldehyde increased and decreased with approximately equal frequency. Average indoor temperatures during winter typically increased after retrofits, usually by less than 1.5 ^{o}C. Dampness and mold, usually based on occupant's reports, almost always decreased after retrofits. Subjectively reported thermal comfort, thermal discomfort, non-asthma respiratory symptoms, general health, and mental health nearly always improved after retrofits. For asthma symptoms, the evidence of improvement slightly outweighed the evidence of worsening. There was insufficient evidence to determine whether changes in thermal comfort and health outcomes varied depending on the type of energy efficiency retrofit. The published research has numerous limitations including a lack of data from retrofits in warm-humid climates and minimal data on changes in objective health outcomes. Suggestions for future research are provided.

Keywords: energy efficiency, indoor environmental quality, residential, retrofit, thermal comfort, health

1.0 INTRODUCTION

Approximately one third of global energy-related emissions of greenhouse gases is attributable to the energy use of buildings, including the energy required to generate the electricity used in buildings [1]. Consequently, reducing building energy use is key among the measures required to limit climate change. Because of the large stock of existing buildings, many with a projected future life of decades, building energy efficiency (EE) retrofits are necessary if we are to obtain sizable near-term reductions in the emissions of greenhouse gases associated with buildings.

A broad range of retrofit measures can be employed to make homes more energy efficient. Sealing air leakage pathways in building envelopes to reduce the rate of uncontrolled air exchange (ventilation) between indoors and outdoors is a very common retrofit measure. Also common are addition of thermal insulation to building envelopes and replacement of existing windows and equipment for space thermal conditioning, water heating and lighting with more efficient equipment. Air sealing of forced air, heating and cooling system ducts is included in many EE retrofit programs.

Many of the EE retrofit measures employed in homes can affect multiple indoor environmental quality (IEQ) parameters, particularly temperature, humidity, air pollutant concentrations, and the occurrence and extent of dampness and mold [2, 3]. Based on mass balance considerations and empirical data, envelope sealing measures that reduce ventilation can be expected to increase indoor concentrations of air pollutants emitted from indoor sources while decreasing indoor concentrations of some outdoor air pollutants. Some EE retrofit programs evaluate the potential for failures in venting of combustion products and include upgrades of venting systems when problems are identified [4]. The materials added to homes during retrofits, such as sealants and insulation, can be sources of indoor air pollutants. For example, thermal insulation materials, and foam sealants and caulks used to reduce uncontrolled air leakage, can emit a variety of volatile organic compounds [5, 6]. Addition of thermal insulation, envelope air sealing, and replacement of windows should make it easier to achieve and maintain acceptable thermal conditions, leading to improved comfort [7]. Insulation and window replacement may also decrease heat exchange by thermal radiation between people and the building envelope, leading to improved thermal comfort, particularly in winter. Indoor air humidity may increase or decrease as a consequence of EE retrofits, depending on whether the outdoor air is humid or dry, the influence of the retrofit on ventilation, and the presence or absence and characteristics of air conditioning or dehumidification systems [8]. The potential for high humidity and condensation within the building envelope or on interior surfaces, which can lead to mold growth, will often be affected by EE retrofit measures, particularly by envelope air sealing and the addition of thermal insulation [9]. Finally, installation of EE measures can disturb existing hazardous materials such as lead paint and asbestos.

Home EE retrofits sometimes incorporate additional measures designed to prevent a deterioration in IEQ or as a remedy to existing deficiencies in IEQ conditions. User-controlled bathroom and/or kitchen exhaust fans are sometimes installed so that moisture, odors, and cooking-related pollutants can be exhausted to outdoors. Also, to maintain a minimum rate of ventilation for the dwelling unit, some retrofits include installation of mechanical ventilation systems designed for continuous, or automated periodic, operation. Some EE retrofit programs include low-cost measures designed to address the source of dampness and mold problems, such as fixing water leaks.

Some home retrofit programs include IEQ improvement as a major goal given approximately equal weight as saving energy. The resulting retrofits are often characterized, in the reviewed studies, as green retrofits, although the term “green retrofits” sometimes has a broader connotation. In addition to implementing the energy saving retrofit measures described above, green retrofits sometimes include installation of continuous mechanical ventilation, integrated pest management practices, replacement of existing components of the homes with components that have lower pollutant emissions, and improvements in particle filtration systems. Water conservation measures may also be included.

EE retrofit measures are often included in programs that focus on reducing very cold conditions and improving warmth, rather than saving energy. Many programs provide heating system upgrades including installation of modern central heating systems that can increase energy use. The programs may include EE retrofits to improve warmth with or without heating upgrades. These programs commonly serve low-income households, often said to be experiencing fuel poverty, with frequent low indoor temperatures during periods of cold weather.

Home EE retrofits have the potential to influence occupant health via several mechanisms [4, 10]. The retrofits may directly or indirectly impact concentrations of health-relevant indoor air contaminants. Changes to indoor temperatures resulting from EE retrofits may affect health. In particular, EE retrofits may decrease the prevalence of homes with frequent and severe low indoor temperatures that are associated with diminished health [11]. By reducing the costs of home heating, retrofits may reduce stress, which is associated with poorer health. Also, with heating and air conditioning costs reduced, the occupants may be able to afford improved foods and better medical care. Home EE retrofits may also reduce outdoor air pollution from electrical power generation and home heating. The potential for changes in health vary. For example, the health of asthmatic residents is more likely to be affected by changes in allergens, respiratory system irritants, and inflammatory agents. Infants, the elderly, and people with preexisting cardiorespiratory conditions may be more affected by changes in indoor temperatures and have an increased susceptibility to air pollution.

This paper reviews research providing empirical data indicating how home EE retrofits influence IEQ conditions, thermal comfort, and self-reported health. Several prior related review articles have been published and these articles are cited in Table S5 within the supplemental information. The prior reviews have identified both non-energy benefits and health risks of EE retrofits, but often the prior reviews have placed an emphasis on either benefits (e.g., Sweitzer et al. 2003 [12]) or on risks (e.g., Bone et al. 2010 [13] and Davies and Oreszczyn 2012 [14]). Some prior reviews have addressed only a single outcome or outcome category, such as the changes in indoor radon concentrations and related health risks (e.g., Lugg 1997 [15]) and some prior reviews have focused on specific types of retrofits, such as retrofits to improve warmth among populations who have been unable to keep their homes warm [16]. One prior review and meta-analysis[17] treated installation of central heating as an EE measure, although this measure may often increase energy use. Another published review [18] assessed the effects of warmth and EE retrofits in homes but did not separately assess the effects of EE retrofits.

The main aim of this review was to determine the influence of EE retrofits of homes on indoor environmental conditions, thermal comfort, and self-reported health. Compared to prior reviews, the present review incorporates the findings of studies described in papers published within the last few years. Additionally, the present paper provides the first reported evaluation of findings as a function of retrofit characteristics. A unique characteristic of this review is the compilation and graphical presentation of reported changes in IEQ conditions, comfort perceptions, and health.

2.0 METHODS

The review was framed around the following questions:

1. How have EE retrofits of homes influenced IEQ conditions (temperatures, indoor contaminant concentrations, presence of dampness and mold), occupant perceptions of thermal comfort, and self-reported occupant health?
2. Does the influence of EE retrofits on IEQ conditions, perceptions, and health vary among the following types of retrofits:
    a. retrofits with energy savings as the sole or dominant goal, with whole house mechanical ventilation not added, and with no focus or minimal focus on implementation of measures to improve IAQ such as pollutant source reduction or particle filtration (basic retrofits);
    b. retrofits with energy savings as the sole or dominant goal, but with continuous or timer-controlled mechanical ventilation systems added to help prevent increases in indoor concentrations of indoor-generated pollutants (ventilation-added retrofits);
    c. retrofits packages designed to save energy and also improve IEQ through addition of various IEQ improvement measures such as improved particle filtration, pest management, water leak reduction, and reduction of sources of volatile organic compounds (green retrofits); and
    d. retrofits with reductions in indoor cold temperatures as the primary goal (warmth retrofits).
3. What are the key gaps and methodological limitations of the existing body of research and what are the implications for future research?

Papers for inclusion in the review were identified through a search on Web of Science using the search string "(home OR house OR residential) AND (energy efficiency OR weatherization OR green building OR passive house) AND (indoor air quality OR health)". There was no restriction based on year of publication or location of the homes. The initial search on January 28, 2019 yielded 1105 results with the earliest publication in 1984. When titles indicated that a paper was potentially relevant to the review, given the outcomes and inclusion and exclusion criteria listed below, the abstract was reviewed. If the abstract indicated that the paper might have relevant data, the full paper was downloaded and read. When data applicable to the review were present, study information and outcome data were compiled in a table. Additionally, the reference lists of papers from which data were extracted, and the reference lists of related review articles, were reviewed by the same process, leading to the inclusion of several additional papers in the review. Subsequent searches using Web of Science, performed in September and November 2019, employing the same search string but restricted to papers published in 2019, yielded no new relevant results.

In the selection of papers, the following inclusion criteria were applied.

1. The study provided empirical data indicating the influence of a home retrofit on one or more of the included outcomes listed below.
2. The retrofit must have included EE measures. EE measures may have been combined with retrofits to improve warmth (that may increase energy use), and/or retrofits intended to improve or maintain indoor environmental quality.
3. The number of retrofit housing units was five or more.
4. The study was described in a paper published in a refereed archival journal published in English. We allowed reports to serve as supplemental information for a published paper.

The following exclusion criteria were also applied:

1. The retrofit was an upgrade or installation of a heating system (often central heat) to improve warmth, without accompanying substantive EE retrofits.
2. The study evaluated outcomes among sets of homes with different levels of EE by initial home design or construction, or with differences not clearly attributable to retrofits.
3. The study evaluated changes in outcomes when subjects moved to new homes.
4. The study was a review, meta-analysis, cost benefit analysis, or discussion that provided no new empirical data. (Improved or expanded analyses of data previously reported were allowed.)
5. The study used models to estimate the influence of EE retrofits on included outcomes, but provided no new empirical data.
6. The retrofit included installation of urea formaldehyde foam insulation (excluded because this type of insulation is no longer used).
7. The study evaluated use of improved, less polluting and more energy efficient, unvented biomass cook stoves in a developing country.
8. The key retrofit was changing from a standard wood stove to a newer, less-polluting, and potentially more energy efficient, wood stove.
9. The study assessed, as a primary goal, the effects of measures to combat extreme heat, which has usually been evaluated via modeling.
10. The study employed an ecological design, with data aggregated across spatial regions but not using data from individual homes.
11. The study collected data only after retrofits and relied on occupants to recall how their health or comfort had changed after retrofits were completed.

The identified published literature included a very large range of outcomes, and many of these outcomes were unique or evaluated in very few papers. For this review, it was necessary to focus on a key set of outcomes for which there were significant empirical data.

The outcomes included in the review were:

1. Indoor, or indoor minus outdoor, concentrations of radon, formaldehyde, volatile organic compounds (VOCs) other than formaldehyde [i.e., TVOC, sum of VOCs, BTEX (benzene,

toluene, ethylbenzene, and xylene), acetaldehyde, or benzene], nitrogen dioxide, and carbon dioxide.
2. Changes in indoor air temperatures.
3. Reported dampness and/or mold.
4. Reported level of thermal comfort or satisfaction with indoor temperature.
5. Reported level of thermal discomfort or dissatisfaction with indoor temperature.
6. Asthma symptoms or other indicators of current asthma.
7. Non-asthma respiratory symptoms.
8. Measures of general health, sometimes called overall health.
9. Measures of mental health.

We initially intended to include indoor particle concentrations as an outcome. However, only three studies meeting inclusion and exclusion criteria were identified and using the methods described subsequently, the particle-related findings from two of these studies were considered weak. Similarly, we initially intended to include satisfaction with indoor air quality as an outcome; however, data were available from only two studies meeting inclusion and exclusion criteria. A list of other excluded outcomes with reasons for the exclusion is provided in Table S1 in the Supplemental Information.

For each included study, characteristics and selected study results were extracted, compiled, and plotted. Compiled characteristics include a brief description of the overall scope and methodology, a study design category, a retrofit type category, a list of included retrofit measures, location(s), the numbers and types of retrofitted and reference buildings and homes, the numbers and types of subjects (e.g., adult, children, low income, asthmatics), whether or not the study was an evaluation of a larger independent retrofit program, and a list of strengths and weaknesses. The study design categories are randomized controlled trial, prospective controlled, prospective uncontrolled, retrospective controlled, and retrospective cross-sectional; the categories are defined in Table S2 of the supplemental information. The retrofit type categories were basic, ventilation-added, green, and warmth retrofits, as defined above. One study [19] included basic retrofits and ventilation-added retrofits and provided separate analyses; thus, the outcomes were compiled separately for the two sub-studies. When a study included both basic retrofits and ventilation-added retrofits and analyzed only the combined data, the study type category was based on the majority type. Since the number of homes or subjects often decreased from pre- to post-retrofit data collection due to attrition, the charts list the smaller of the number of homes or subjects. The compilation includes strengths and weaknesses using the criteria in Table 1.

Table 1. Categories of study strengths and weaknesses.

Strength Terms	**Definitions**
Large study	50 or more housing units were retrofit. If a retrospective cross-sectional study with number of retrofit homes not indicated, the study included at least 300 homes
Large population	Health or perception data were obtained from 100 or more subjects from retrofit homes.
Reference housing units	Study collected data from reference housing units (not retrofit) contemporaneous with data collection in retrofit units. Reference and retrofit units and populations were similar in characteristics that may influence the studied outcomes.
Randomization	Random assignment of homes to intervention versus reference group.
Paired data	Study, or a portion of study analysis, assessed changes in outcomes based solely on data available from homes, or subjects, that provided data both before and after retrofits.
Control for confounding	A multivariate model was employed to control for potential confounding.
Weakness Terms	**Definitions**
Small study	Study, or specific outcomes, were based on retrofits of 10 or fewer housing units.
Small population	Health or perception data were obtained from 20 or fewer subjects from homes with retrofits.
Lack of reference housing units	No reference housing units or fewer than five reference housing units.

Reliance on unpaired data	Study compared outcomes based on data before and after retrofits. The data were obtained from different, but overlapping, sets of homes. Typically, post-retrofit data were available from fewer homes because some participants dropped out of the study, but the full set of pre-retrofit and post-retrofit data were used to assess the influence of the interventions.
Short monitoring periods	Measured IEQ data were based on 24 or fewer hours of data collection. For NO_2, no accounting for variations in outdoor variations affecting indoor levels.
Seasonal mismatch	Evidence that pre-retrofit and post-retrofit data were not collected in the same season.
Lack of statistical analysis	Study did not include statistical analysis of differences in outcomes.
Failure to use reference data in statistical tests	While the study collected reference data from homes that were not retrofit, changes in outcomes among the retrofit homes were not adjusted for, or statistically compared with, changes in outcomes in the control homes.
No control for confounding	The lack of data analysis methods to control for potential confounding was considered a weakness in retrospective cross-sectional studies.

One important additional, but unadvoidable, weakness, common to all studies, was a lack of blinding of the occupants; i.e., occupants were aware of the retrofits.

Also compiled for each included study are details related to the outcomes specified above. As available, the compilation includes the measured percent changes in the outcomes, the numbers of retrofit homes and the numbers of reference homes. Reference homes were homes similar to those that were retrofit from which data were collected in order to determine the extent of outcome changes in non-retrofit homes. The compilations include, when available, the number of subjects that provided outcome data, and whether or not any changes in outcomes were known to be statistically significant based on criteria of $p < 0.05$ or 95% confidence limits excluding unity. If not provided in the reviewed papers, percent changes were calculated from the pre- and post-retrofit outcomes. The calculated percent changes were relative to the pre-retrofit outcome values. For example, if 20% of subjects had a health effect prior to retrofits and 10% had the health effect after retrofits, and there was no reference group or no change in the reference group, the percent change is 50%. With one exception, percent changes in outcome data collected from reference homes were calculated in the same manner and subtracted from the percent changes of the intervention homes. The exception was the calculations of percent changes in indoor pollutant concentrations in Lithuania[20]. There were few reference homes in Lithuania, and post-retrofit data were unavailable from up to two thirds of the reference homes, making the reference data unreliable. When an original study result was presented as an odds ratio, the percent change was calculated as the difference between unity and the odds ratio. For example, an odds ratio of 1.3 was considered as a change of 30%. We recognize that, based on the definition of odds ratio [21], the actual percent changes will be smaller; but typically only moderately smaller. Most studies used the arithmetic average (mean) as the indicator of central tendency, with median or geometric mean employed in a few studies. For consistency, percent changes were based on arithmetic averages when possible. Even large percent changes in initially low contaminant concentrations or in an initially small health outcome prevalence may be medically unimportant. Consequently, we examined each instance with a percent change in an outcome greater than 80% and point out to readers when the initial contaminant concentration or health outcome prevalence was low.

For two reasons, our calculated, tabulated, and plotted percent changes in outcomes sometimes differed from percent changes reported in the original papers. First, some papers reported absolute percentage changes. Again using the example of 20% of subjects having a health effect prior to retrofits and 10% of the subjects having the health effect after retrofits, the absolute percent change equals 20% minus 10% or 10%, while the relative percent change is 20% minus 10% divided by 20% or 50%. Second, when data were available, we subtracted the percent changes in outcomes within reference homes, while the authors sometimes neglected the changes in reference homes. In a few instances, after subtracting the percent changes in reference homes, the calculated percent reduction in an outcome exceeded 100%. Since reductions cannot, in reality exceed 100%, these were shown as 100% reductions in plots. Our assignment of statistical significance sometimes differed from those in the original reports. Some papers with data from both retrofit homes and reference homes reported statistically significant changes in outcomes in homes with retrofits, but did not determine if the changes in outcomes in retrofit homes were statistically significantly different from the changes in reference homes. In these instances, we considered the net percent change in an outcome to have an unknown statistical significance.

Because strengths and weaknesses often varied among the multiple findings of individual studies, the overall strength of each finding was separately estimated on a four-level scale of 0, 1, 2, 3. A rating of zero was assigned to outcomes considered too weak to include in plots. A rating of one indicates a weak finding considered worthy of inclusion in plots and a rating of three indicated a strong finding. A rating of two was assigned to findings that have some substantial strengths and few or no critical weaknesses. The subjective strength estimates were developed independently by each author of this paper, considering the study type category, the numbers of buildings and subjects, and the methods used to collect and analyze the outcome data. Any findings that were rated differently by two or more authors were discussed and reassessed by each author until a consensus was reached. A rating of weak was always assigned for findings based on retrofits of five or fewer homes and findings based on 20 or fewer subjects. Weak ratings were also assigned when measurement periods were short, e.g., 1 h or 1 day. For a strong rating, we typically required either a prospective study design with assessments before and after retrofits in at least 30 homes, or a cross-sectional design with hundreds of homes in the survey and multivariate analyses to control for potential confounding, plus no critical weaknesses.

Because of the high diversity in outcome metrics, study methods, home types, and subjects, formal statistical meta-analyses were not appropriate. Consequently, the interpretation of the compiled findings for each outcome is subjective. For the interpretation, the authors considered the quantity, consistency, and strength ratings of findings as well as the magnitudes and statistical significance of the changes in outcomes attributable to retrofits. Also, objective outcomes, based on measurements, were considered to be generally more reliable than subjective outcomes based on surveys and questionnaires.

3.0 RESULTS

Tables S3 and S4 in the supplemental information provide the information extracted to characterize studies and study findings.

Data were extracted and included in this paper from 36 studies. These were described in 44 papers plus two reports treated as equivalent to supplemental information, with up to five papers providing results of a study. The extracted and included data represented 15 studies of basic retrofits [4, 8, 10, 19, 20, 22-36], four studies of ventilation-added retrofits [19, 37-40], four studies of green retrofits [41-45], and 13 studies of warmth retrofits [7, 46-59]. Most of the studies were conducted in the United States or Europe, with two studies in New Zealand [7, 50]. Nearly all studies took place in locations with cold winter climates and the majority of data were collected in winter, with the following exceptions: a study in Phoenix, Arizona [42] which has hot, dry summers and mild winters and conducted sampling in the summers; a large study of the U.S. Weatherization Assistance Program [10] which included regions with mild winter weather and sampled year-round; and a study in North Carolina [40] which has relatively mild winter weather and collected data in both cooling and heating seasons. Prospective uncontrolled studies and prospective controlled studies were the most common. Studies varied widely in size. For example, the number of retrofit homes providing both pre- and post-retrofit data in prospective studies varied from seven [56] to 1,987 [46] with some outcomes based on data from as few as four or five retrofit homes [20, 45]. One cross-sectional study was based on data from a sample of 73,500 homes [33]. Health and perception outcomes were based on as few as seven subjects [60] and as many as 3,241 subjects in the cross sectional study of Engvall, Norrby [35]. Thermal comfort outcomes of Gilbertson, Grimsley [46] were based on 2,685 subjects that provided data before and after retrofits. Health outcome data were entirely self-reported except for blood pressure and death, addressed in too few papers for inclusion in this review (see Table S5 descriptions of excluded papers). Excluding three retrospective studies focusing on changes in radon concentrations, all but five studies focused on retrofits of housing with low income residents, with low income defined by the authors of the reviewed papers using theier local criteria. Four studies, described in eight papers, included no mention of a focus on low income housing [8, 20, 23-26, 30, 35]. In a fifth study, approximately half of subjects resided in social (low-income) housing.Table S5 in the supplemental information lists papers that include related content but were excluded for the reasons noted. Most of the excluded papers were review or discussion articles, model-based evaluations of retrofits, or did not provide data for outcomes included in this review.

The retrofits implemented varied among studies and are described, for each study, in Table S3 within the supplemental information. Some studies applied national or regional protocols for retrofit selection, as indicated in Table S3, while in other studies, the research team selected retrofits without reference to an external protocol. In studies assigned to the "basic retrofit" category, 86% added thermal insulation, 71% replaced windows, 57% sealed leaks in envelopes (not including window replacement), and 50% modified or replaced space conditioning systems. Other retrofit measures were implemented in few studies. The retrofits of all studies assigned to the "ventilation added" retrofit category included addition of continuous or timer-controlled mechanical ventilation systems. All "ventilation added"studies also added thermal insulation in some or all homes, 50% of studies sealed envelopes, and 50% upgraded or replaced heating systems. The energy savings retrofit measures in studies assigned to the "green-retrofit" category were not always described. Envelope sealing, window or door replacement, and space conditioning upgrades were common. One study added continuous mechanical ventilation in all retrofit homes and anothor study added continuous mechanical ventilation in half of homes. Seventy five percent of studies added kitchen and/or bath fans and 75% took measures to reduce water leaks. Half of studies included pest control measures and half installed new low VOC products such as flooring, cabinets, or countertops. Of studies assigned to the "warmth retrofit" category, 70% added or upgraded heating systems. One study, did not describe the energy efficiency retrofit measures. Among the remaining studies, all added thermal insulation, one third replaced windows or doors, and one third sealed envelopes.

Figure 1 shows a key for interpreting subsequent figures. In the subsequent figures, results from the same study are grouped and a dashed line seperates data from distinct studies. Results are grouped by type of retrofit, e.g. basic retrofit, green retrofit, etc. with the retrofit types indicated by the background colors in Figure 1. When percent changes were determined, they are indicated by the length of a horizontal bar. Triangles indicate the direction of changes that could not be determined quantitatively from the reported data. Green indicates improvement and orange/pink indicates worsening. Dark bar coloring is used for findings known to be statistically significant based on $p < 0.05$ or a 95% confidence interval excluding unity. Light bar coloring is used when findings are not statistically significant or when information on statistical significance was not available. A circle denotes a 0% change and a diamond is used for outcomes that were reported by authors as not statistically significant without a magnitude or even a direction reported. The tabulated data includes the numbers of retrofit homes or the numbers of subjects from retrofit homes from which the outcomes were determined. When these numbers varied, for example when post retrofit data were obtained from fewer homes or subjects, the smaller number is provided. For quantified non-statistically-significant changes in outcomes, p values are provided when available. Finally, the letters "S" and "W" denote findings with consensus ratings of strong (consensus rating = 3) and weak (consensus rating 1), respectively. The absence of a "S" or "W" label indicates a consensus rating of 2. This method of plotting findings reflects limitations in the reported data. Few studies reported confidence intervals. Also, for most findings, particularly those that were reported as not statistically significant, p values were not provided.

In viewing the figures, readers should understand that multiple results from the same study are, in many cases, not fully independent. This fact was considered as we sought to identify trends.

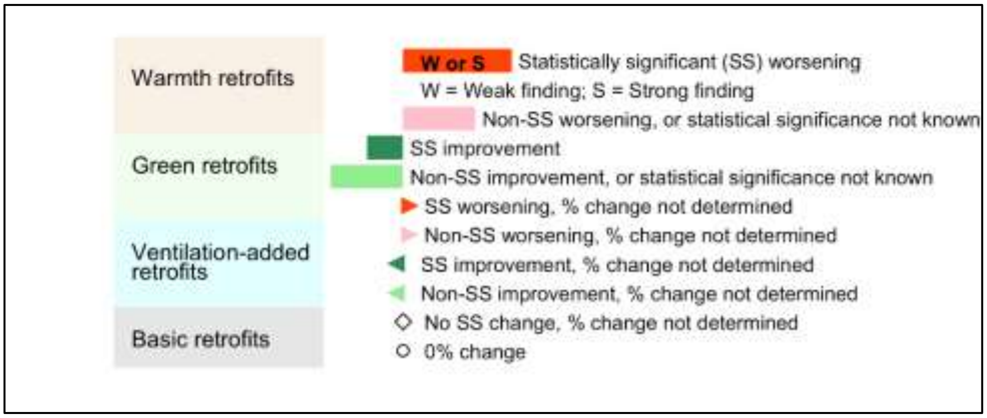

Figure 1. Key to subsequent figures.

Figures 2 – 6 illustrate the reported changes in indoor contaminant concentrations associated with retrofits. Results for radon are shown in Figure 2. The primary source of indoor radon is usually the soil surrounding a building, with building materials and water sometimes also significant sources [61]. Higher indoor radon concentrations are associated with increases in lung cancer [62] and the U.S. EPA has established a guideline of 148 Bq m^{-3} for radon [63]. As indicated in Figure 2, increases in indoor concentrations after retrofits were more common than decreases in indoor concentrations, with most data from studies with basic retrofits. Five studies reported only increases in indoor radon, three studies reported only decreases in indoor radon, and three studies reported both increases and decreases in indoor radon. Study-average radon increases varied from a few percent to more than 100% and average decreases varied from a few percent to almost 50%. Only one of the decreases in indoor radon was statistically significant, and the radon concentrations in this study [40] were very low. Excluding studies with weak findings for radon, reported average increases in indoor radon substantially exceeded average decreases. All strong findings indicate increases in radon concentrations. Only two studies with ventilated-added retrofits reported changes in radon concentrations. The plot includes an average 115% increase in radon in four homes in Lithuania that had focused energy retrofits out of 33 total homes retrofit. The initial radon concentrations in these homes averaged 21 Bq m^{-3}, which is well below health-based guidelines for radon but was typical of initial radon concentrations in Lithuanian homes within this study. The radon data also include a 130% average increase in a set of 114 homes and an 81% increase in a set of 3794 homes. The 130% increase corresponds to a 56 Bq m^{-3} average increase which is large enough to be important, i.e., approximately 40% of the US EPA's guideline value for radon [63]. The 81% increase, corresponding to approximately a 65 Bq m^{-3} increase in a geometric mean radon concentration, was also large enough to be important.

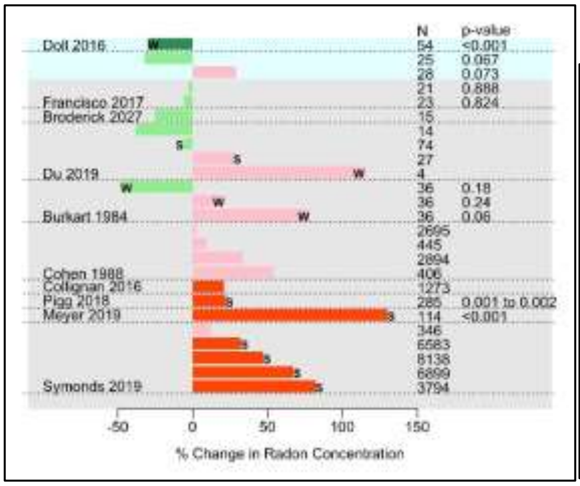

Figure 2. Changes in indoor radon concentrations.

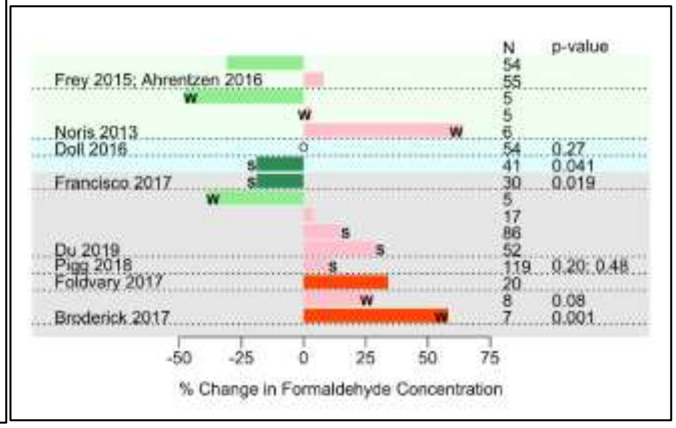

Figure 3. Changes in indoor formaldehyde concentrations.

The findings for formaldehyde are depicted in Figure 3. Building materials and furnishings are key indoor sources of formaldehyde [64]. Formaldehyde is a mucous membrane irritant [65] and a probable human carcinogen [66, 67]. The concentration limits in formaldehyde guidelines vary widely [64] from 0.002 to 0.1 ppm as annual averages. This broad range indicates a lack of agreement about the potential of low formaldehyde concentrations to adversely affect health. The data indicate a tendency for formaldehyde concentrations to increase after basic retrofits. Considering all retrofit types, there are more instances of increased indoor formaldehyde than decreased indoor formaldehyde, with the majority of findings not statistically significant. Six studies reported increases in indoor formaldehyde. Five studies reported decreases in indoor formaldehyde, with three of the five studies also reporting increases in formaldehyde. If weak findings are neglected, four studies found decreases and four found increases in formaldehyde. The strong findings include 29%, 15%, and 10% increases in formaldehyde and two 19% decreases.

Figure 4 shows the findings for VOCs other than formaldehyde. Overall, there are about equal numbers of increases and decreases of indoor VOC concentrations. Six studies reported increases in VOCs and four reported decreases. For basic retrofits, increases substantially outnumber decreases. For green retrofits, VOC concentration decreases predominate, but most data are from a single small study with a weak rating. More than half of the VOC findings are not statistically significant or have an unknown statistical significance. Many findings were assessed as weak, only two received a strong rating. There are insufficient data to determine whether the changes in indoor VOC concentrations vary depending upon the type of retrofit.

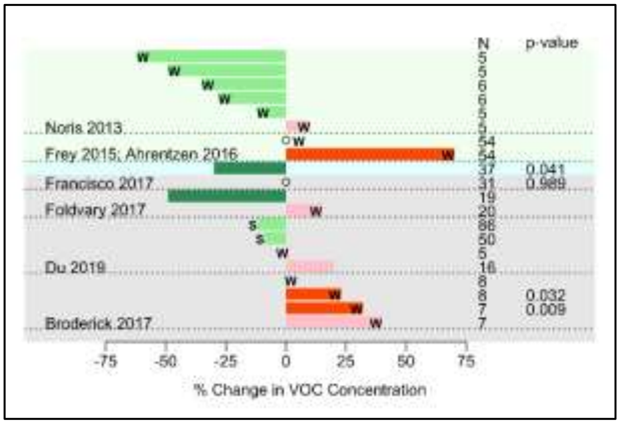

Figure 4. Changes in indoor VOCs other than formaldehyde

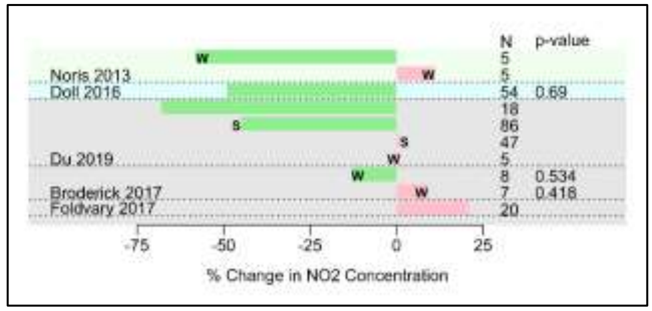

Figure 5. Changes in indoor nitrogen dioxide concentrations.

Nitrogen dioxide (NO_2) is a respiratory irritant and can aggravate asthma [68]. NO_2 indoors comes from outdoor air and from indoor combustion sources, when present. The U.S. EPA standard for NO_2 in outdoor air is 100 ppb as a one hour average and 53 ppb as an annual average [69]. Changes in NO_2 concentrations associated with residential retrofits are depicted in Figure 5, with data available from only five studies. Equal numbers of studies reported increases and decreases with the reported decreases generally larger in magnitude. None of the changes were reported to be statistically significant. About half of findings were rated as weak. With or without the weak findings, the data are insufficient for conclusions about the influence of retrofits on indoor NO_2.

Indoor carbon dioxide (CO_2) comes from outdoor air and from the exhaled breath of occupants. Unvented combustion appliances can also be a source of indoor CO_2. It is not clear whether CO_2 should be considered a pollutant or just an indicator of ventilation rate per person [70]. The findings for CO_2 are provided in Figure 6. The data, available from only six studies, include increases and decreases in indoor concentrations. The three ventilation-added and green retrofit studies that added continuous mechanical ventilation during retrofits all reported decreases in CO_2. A majority of findings from basic retrofits are increases in indoor concentrations, but many of these increases are from a single study and all are statistically insignificant or have an unknown statistical significance [26]. All findings with a strong rating are moderate in size, i.e., 3% to 16% decreases in indoor CO_2.

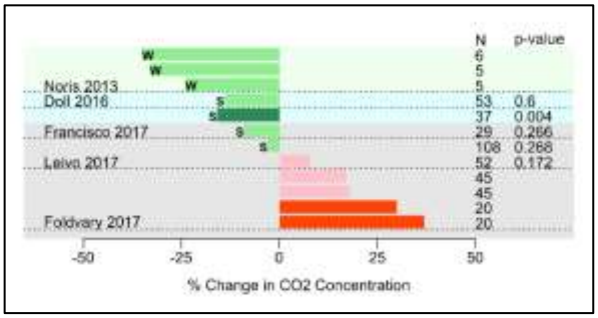

Figure 6. Changes in indoor carbon dioxide concentrations.

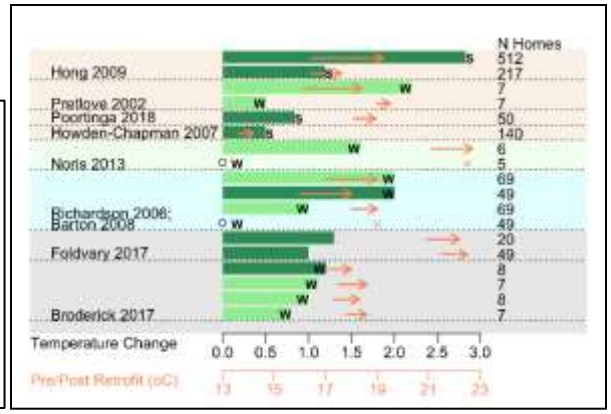

Figure 7. Changes in indoor temperatures in winter.

Figure 7 shows changes in indoor temperature from data collected in winter before and after retrofits. The shaded bars indicate temperature changes, with a “o” symbol denoting no temperature change. The base and head of each arrow indicate the pre-retrofit and post-retrofit average temperatures. If pre- and post-retrofit average temperetures were the same, the values were marked by an “x” symbol. Two studies did not report the duration of temperature measurements. Among the six remaining studies, pre- and post-retrofit measurement periods were one week or longer in four studies [26, 45, 49, 54], 24 h in one study [22], and 1 h in the final study [37]. Measurement details, when available, are provided in Table S3 in the supplemental information. The results have not been adjusted to account for any differences in outdoor temperatures between the pre-retrofit and post-retrofit measurement periods which might have influenced indoor temperatures. Two studies reported no change in average winter indoor temperatures associated with retrofits. In all other instances, mean indoor temperatures during winter increased after retrofits or were higher in homes that had been retrofit. Most studies reported mean increases across the retrofit homes of less than 1.5 ^{o}C. Even with warmth retrofits, which had increased indoor temperatures as the primary objective, most sample-average temperature increases were less than 2 ^{o}C. Only about half of the temperature increases were statistically significant. Many of the findings received a weak strength rating, often because of short periods of temperature measurement. The temperature increases with a strong strength rating ranged from 0.5 ^{o}C to 2.8 ^{o}C. The 0.6 ^{o}C increases in annual average indoor minus outdoor temperatures reported in a study from New Zealand [50] are not included in Figure 7 because they do not necessarily indicate changes in indoor temperatures.

Several studies reported changes in indoor relative humidity associated with home EE retrofits (results not shown). The reported changes are all small, typically a few percent, and are unlikely to be important.

Dampness and mold in homes are associated with increased respiratory health effects including asthma symptoms [71]. Changes in dampness and mold associated with retrofits are depicted in Figure 8. Except in one study [37] with instrumentation used to measure dampness of walls, the data were based on visual observations, mostly provided by occupants. In nearly all instances, regardless of the type of retrofit, reported dampness and mold diminished after retrofits and often diminished by 40% or more. A majority of findings are statistically significant. In the case of the single statistically significant increase within Figure 8, dampness decreased in both the retrofit homes and the reference homes, but the relative percentage decrease was larger in reference homes. The reference home population was not ideal because it had an substantially lower initial prevalence of dampness than the retrofit homes. All strong findings indicate reductions in dampness and mold in homes with warmth retrofits, except for one small, statistically insignificant increase. The dampness and mold results include five findings with reported decreases of 80% or larger. In four of the findings, the initial prevalence of dampness and mold was well over 50%; thus, the large percentage decreases are important. In the fifth instance, a 100% decrease, dampness was assessed by measuring the moisture levels in walls and the finding is a consequence of approximately a 30% decrease in intervention homes coupled with approximately an 80% increase in reference homes.

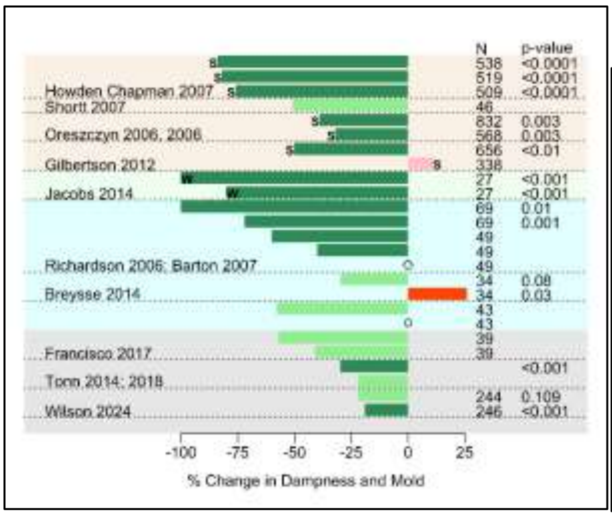

Figure 8. Changes in dampness and mold.

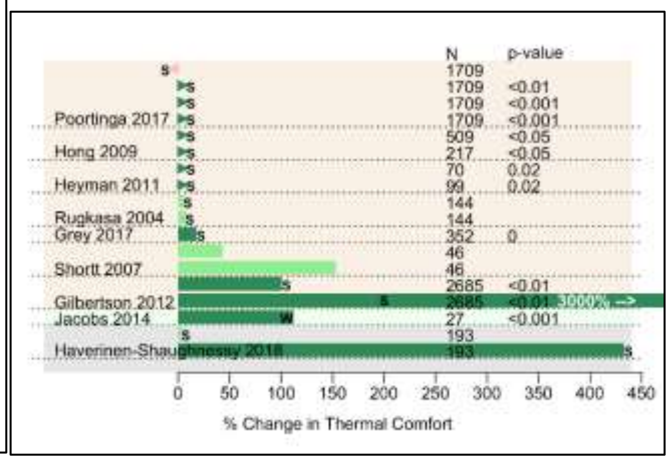

Figure 9. Changes in thermal comfort.

Figure 9 shows the reported changes in self-assessed thermal comfort, with the majority of data from studies of warmth retrofits. Improvements in thermal comfort dominate with only one result indicating a non-statistically significant worsening. A majority of the improvements are statistically significant. In some cases, a very small fraction of subjects reported comfort prior to retrofits and a substantial fraction of subjects were comfortable after retrofits, leading to very large percentage increases in thermal comfort.

Several studies assessed changes in measures of thermal discomfort, again with most data from studies of warmth retrofits. All findings, depicted in Figure 10, indicate a reduction in thermal discomfort, with many reductions greater than 40%. There are three instances in which thermal discomfort decreased by more than 80%. In one of these instances, the pre-retrofit prevalence of discomfort was high, approximately 72%. In the other two instances, pre-retrofit levels of discomfort were not provided.

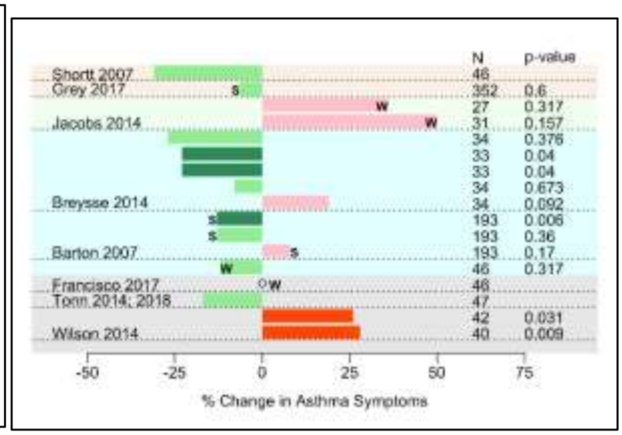

Figure10. Changes in thermal discomfort.

Figure 11. Changes in asthma symptoms.

Changes in asthma symptoms are shown in Figure 11. Specific asthma symptom metrics included any recent symptoms, summed scores on asthma symptom surveys and the number of symptom free days (or nights) in the prior two weeks – for adults, children or both. Findings of reduced symptoms moderately outnumber findings of increased symptoms, although more of the reductions in symptoms are far from statistically significant. Two studies reported increases in both of their metrics for asthma symptoms and four studies reported only decreases in their single metric of asthma symptoms Two other studies reported mixed results, with an increase in one metric and decreases in others metrics of asthma symptoms. One study reported no change in symptoms. Excluding the weak findings of the green retrofit study, most of the assessed asthma symptoms decreased following retrofits that added ventilation or focused on warmth. Except for two weak findings, all changes in asthma symptoms were modest reductions or increases of 31% or less.

Figure 12 shows the changes in non-asthma respiratory outcomes, which include unspecified respiratory symptoms, hay fever, respiratory allergy, sinusitis, cough, nasal symptoms, throat irritation, cold or flu symptoms, and, in one study, wheeze. In nearly all instances, regardless of the type of retrofit, the outcomes decreased (improved) after retrofits. Many of the improvements were rated as weak and five of the improvements have p values of 0.32 or higher. Even if all weak findings are excluded from consideration, the remaining data suggest overall improvements in non-asthma respiratory outcomes after retrofits. Three studies have strong findings showing improvements in this outcome, with one of these studies also having a strongly rated worsening of this outcome. One study reported two 100% decreases in non-asthma respiratory outcomes; however, these decreases were the result of only a few subjects who reported the outcomes initially but not after the retrofits.

Several studies assessed changes in general health or overall health, often based on scores from a set of health questions or on a single question asking about overall health. The findings are depicted in Figure 13. Eight studies have findings of improved general health, with one of these studies also reporting instances of worse general health. Two findings with a strong rating, from a single study, indicate worsened general health, compared to five strong findings of improved general health from three studies. Most of the changes are modest in magnitude, less than 20%. The single statistically significant worsening in general health appears to be an outlier and no poterntial explanation for its outlier status was identified.

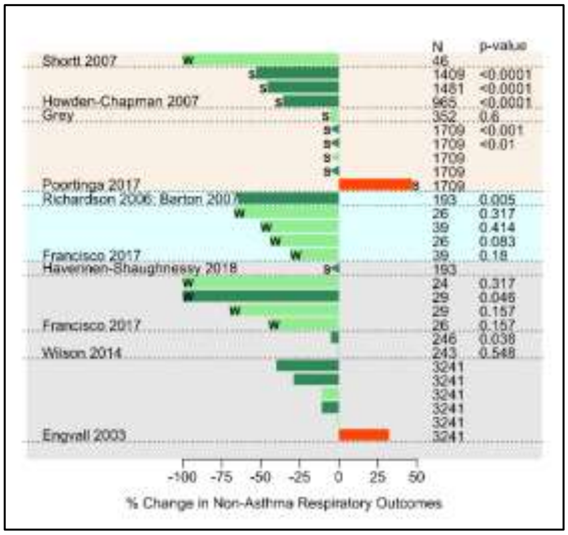

Figure 12. Changes in non-asthma respiratory outcomes.

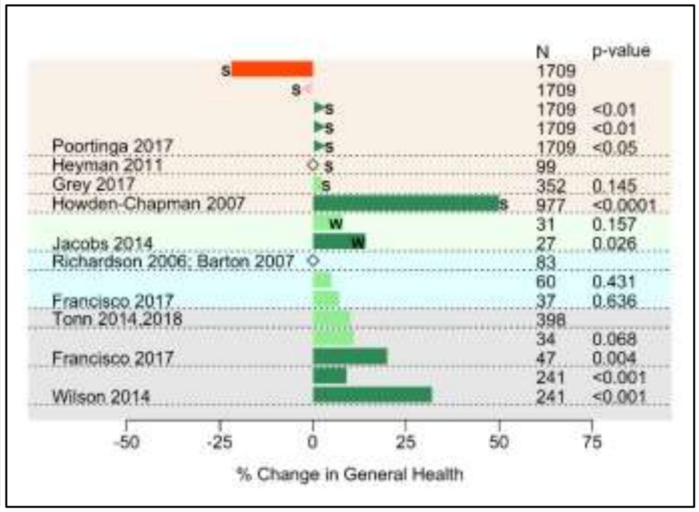

Figure 13. Changes in general health.

The final outcome in this review is mental health, with results in Figure 14. The mental health category includes a variety of metrics such as distress scores, strength and difficulty scores, stress scores, and anxiety and depression scales. Every finding, except one, indicates an improvement or no statistically significant change in mental health. Many of the findings were rated as weak and the large number of results from just a few studies makes the evidence of mental health improvement appear stronger than may be warranted. All strong findings are from studies of warmth retrofits and all indicate improvement in mental health. The one very large percentage change in a mental health outcome is a consequence of calculating a percentage change when the pre-retrofit value (i.e., denominator) is very small.

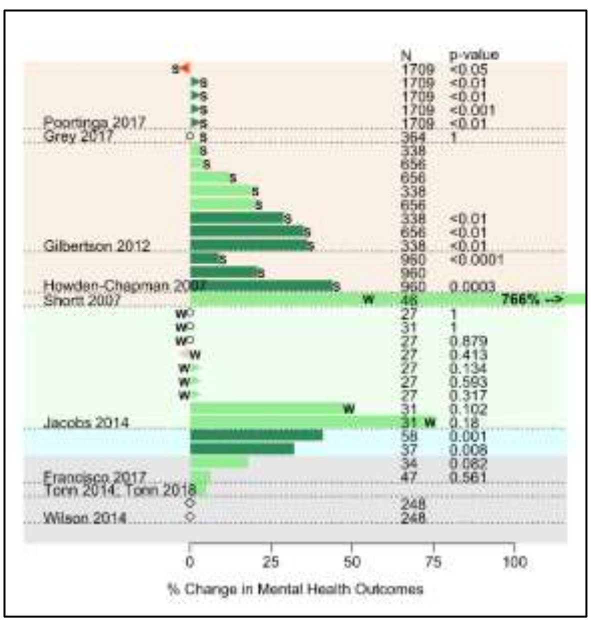

Figure 14. Changes in mental health outcomes.

4.0 DISCUSSION

The objectively-measured outcomes considered in this review are air contaminant concentrations and temperatures. For most of the air contaminants which have been assessed in the literature, there is not a consistent and clear direction or magnitude of the impact of retrofits. The direction is most clear for radon, which has mostly been found to increase after retrofits. The expected health impact of increasing radon in homes is an increase in the risk of lung cancer [63]. However, it is important to note that only two studies assessed radon changes for retrofits with added ventilation, which is required now in many government-managed retrofit programs. For formaldehyde, there is a tendency for indoor concentrations to increase after basic retrofits; however, the data are limited. For other VOCs and nitrogen dioxide, the review provides no strong evidence of an overall tendency for either increases or decreases in indoor concentrations after retrofits. The very limited data on carbon dioxide suggest increases in concentrations after basic retrofits and decreases after ventilation-added and green retrofits, but the data are not sufficient for conclusions. Post-retrofit indoor temperatures in winter are typically increased relative to pre-retrofit indoor temperatures, with most increases less than 1.5 ^{o}C on average. Because low indoor temperatures are associated with poorer health [11], and much of the data are from homes with initially low indoor temperatures that received warmth retrofits, health improvements are expected from an increase in indoor temperature.

The subjective outcomes of this review are the reports of dampness and mold (subjective in all but one study), the reported levels of thermal comfort and discomfort, and the indications of health status (general health, mental health, asthma symptoms, non-asthma respiratory symptoms). The reviewed data indicate a tendency for every subjective outcome, except possibly asthma symptoms, to improve after retrofits, regardless of the type of retrofit. The reductions in dampness and mold are often greater than 40%, the improvements in thermal comfort, when quantified, are always greater than 80%, and the improvements in thermal discomfort, when quantified, range from 28% to 94%. For asthma symptoms, no clear trend of improvement or worsening after retrofits is evident and most study findings that were rated as moderate or strong were changes of less than 30%. Non-asthma respiratory outcomes and general health typically improved after retrofits, regardless of the type of retrofit, and mental health changes, when quantified, were always improvements. The magnitudes of changes in non-asthma respiratory outcomes, general health, and mental health were highly variable.

Because most data were collected in winter, the general improvements in subjectively reported thermal comfort and discomfort are directionally consistent with the measured increases in indoor temperatures during winter. Also, improvements in winter time comfort and increases in indoor temperature are consistent with expectations after retrofits that often improved thermal insulation, reduced envelope air leaks, and sometimes improved heating systems. Improvements in dampness and mold were not likely a consequence of changes in indoor humidity, because relative humidity typically changed by only a few percent and was never particularly high. The improvements in dampness and mold might be partly a consequence of repairs that eliminated water leaks –repairs were mentioned in some papers. Also, the addition of thermal insulation to building envelopes and the increases in indoor temperatures likely reduced the prevalence of cold indoor envelope surfaces on which mold may grow.

The tendency for formaldehyde concentrations to be higher after basic retrofits is consistent with expectations. Basic retrofits typically include envelope sealing to reduce ventilation rates, which would be expected to increase indoor concentrations of formaldehyde, for which indoor sources dominate. Also, post-retrofit increases in indoor temperature could contribute to formaldehyde concentration increases because formaldehyde emission rates increase with temperature. The increases in indoor CO_2 levels after basic retrofits that tend to decrease ventilation rates is consistent with expectations based on mass balances. The decreases in indoor CO_2 after ventilation added and green retrofits might be explained by addition of mechanical ventilation leading to increased ventilation rates. The lack of strong trends in the changes in indoor concentrations of NO_2 and VOCs other than formaldehyde might be a consequence of the presence of both indoor and outdoor sources of these contaminants.

The general trend toward improvements in health after retrofits is not explained by the measured changes in pollutant concentrations, because concentrations did not tend to decrease. The increases in temperature and reductions in dampness might partially explain the improvements in health. Also, other indoor environmental changes not included in this review, such as reductions in cockroaches and rodents, might help explain some of the health improvements. Reductions in energy costs after retrofits might help to explain improvements in stress-related aspects of mental health. However, we must consider another potential explanation for the improvements in health. The occupants were aware of the retrofits and often received no-cost upgrades to their homes. Occupants of some of the more recent studies may have been told that EE upgrades improve indoor environmental conditions and health. Thus, there is a possibility that a reporting bias could have contributed to the improvements in self-reported health and even the improvements in self-reported thermal comfort and dampness and mold. As evidence, we note that one study [55] found new kitchens or bathrooms associated with improvements in health.

There are many limitations to the available data. Nearly all data are from retrofits of homes with low income occupants, located in the United States and Europe. Few studies mention any verification that the retrofits were implemented as intended. Dampness and mold problems were often present in a majority of homes and many of the studies took place in homes with very low pre-retrofit indoor temperatures. Several papers report cockroach and rodent problems. Thus, many of the findings of this review may not be applicable to homes with higher-income residents with fewer IEQ problems. With few exceptions, the reviewed studies were from locations with cold winter climates and most data were collected in winter. The findings may not apply to retrofits in warmer climates and may not reflect changes in summertime indoor environmental conditions. The absence of significant thermal comfort findings and indoor temperature changes during periods of warm weather is an important limitation. Most of the studies in the review evaluated government-managed retrofit programs or retrofits implemented by the research team. Thus, findings may not be applicable to private sector home EE retrofits, which may place a different level of priority on protecting indoor air quality. The small number of studies for many outcomes and retrofit types is another limitation. For example, relatively few studies reported results of ventilation-added retrofits. The health data in this review were entirely subjective and subject to reporting bias, and occupants were aware of the retrofits. Also, a variety of metrics have been used within health outcome categories. In particular, the general health and mental health metrics vary among studies. Consistently used outcome metrics would have been preferable.

There were deficiencies common to many of the studies included in the review. Many studies failed to include reference homes that received no retrofits. Even when reference homes were included, the data from reference homes were often not used in the statistical analyses. Short periods of monitoring of indoor environmental conditions were common and the resulting data may not have been representative of the longer time periods most relevant to the outcomes assessed. In some studies, the combination of short monitoring periods and modest numbers of retrofit homes resulted in low power to assess how retrofits influenced indoor contaminant concentrations. Comparisons of pre-retrofit and post-retrofit conditions often relied on unpaired data; for example, on data before retrofits from homes or subjects that provided no post-retrofit data. Many studies had a small size and consequently low statistical power. Power was particularly low to detect changes in outcomes, such as asthma symptoms, that affected only a small subset of the study populations. In nearly all studies, post retrofit data were collected within two years, and most often within one year, of the retrofit implementation. The extent to which retrofits lead to persistent changes in IEQ conditions was not assessed in the reviewed studies. Also, the reviewed studies were not able to detect changes in health that occur only after many years of changed pollutant exposure.

Research not included in this review may provide additional information about the influence of home EE on IEQ and health. There have been studies of the IEQ and health implications of new energy-efficient construction, e.g., Wallner et al. 2015 [72], although finding suitable sets of new non-energy efficient reference homes, well matched to the energy efficient homes, is a challenge. There have been studies of how ventilation rates or envelope air tightness in homes influences levels of indoor air pollutants and health, e.g., Lajoie et al. [73] and Shrestha et al. 2019 [74]. The health consequences of cold homes and of dampness and mold in homes have been studied. Finally, a few studies have evaluated how IEQ or health vary depending on home energy efficiency ratings. None of this literature was evaluated in the present review. Table S2 in the supplemental information lists papers pertaining to some of these topics.

The study findings, limitations, and deficiencies have implications for future research. In particular, more research is needed to evaluate private sector home EE retrofits, retrofits in warm-humid climates, retrofits of homes not occupied by low income residents, and retrofits outside of the United States and Europe. More data are needed to assess how the retrofits affect indoor particle concentrations and perceived indoor air quality. Given the high potential for reporting bias in subjective health outcomes when occupants cannot be blinded, increased collection of objective health data is recommended. Some of the studies of how retrofits affect radon concentrations were performed more than 20 years ago and newer data would be helpful. Given the evidence of radon concentration increases after retrofits, we also suggest research on radon mitigation measures that are effective and practical to implement during EE retrofits. In general, future studies should include non-retrofit reference homes and evaluate changes in IEQ and comfort and health outcomes in retrofit homes relative to changes in the same outcomes in reference homes. Also, monitoring periods for IEQ conditions should be sufficient to minimize the influence of day-to day variability in occupancy, occupant activities, and weather.

5.0 CONCLUSIONS

The following conclusions are based on this review of empirical data from evaluations of residential EE retrofits:

1. Indoor radon concentrations tended to increase after basic retrofits.

2. There is a tendency for formaldehyde concentrations to be higher after basic retrofits; however, the associated data are limited.

2. After retrofits, concentrations of VOCs other than formaldehyde and nitrogen dioxide have increased and decreased with approximately equal frequency.

3. Carbon dioxide concentrations tended to increase after basic retrofits and decrease after ventilation-added and green retrofits, but the associated data are very limited.

4. Mean indoor temperatures during winter have typically increased, usually by less than 1.5 ^{o}C.

5. Indoor dampness and mold, usually based on reports of occupants, have decreased in a large majority of studies.

6. Subjectively reported outcomes, including thermal comfort, thermal discomfort, asthma symptoms, non-asthma respiratory symptoms, general health, and mental health have generally improved after retrofits, with only weak evidence of improvement of asthma symptoms. The evidence of post-retrofit improvements in thermal comfort in winter is particularly consistent.

7. There are insufficient quality data to determine, with certainty, whether changes in the comfort and health outcomes vary depending on the type of EE retrofit.

6.0 ACKNOWLEDGMENTS

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Association of Residential Energy Efficiency Retrofits with Indoor Environmental Quality, Comfort, and Health: A Review of Empirical Data

Supplemental Information

March 1, 2020

Table S1. Excluded outcomes.

Excluded outcome	**Reason for exclusion**
Allergens in dust	Minimal data
Carbon monoxide	Minimal data and concentrations were too low to be consequential
Fungi and bacteria in air and dust	Minimal data, also airborne levels have been shown to be very highly temporally variable; thus, short term samples are not informative for the purposes of this review
Dust mites in dust	Minimal data
Black carbon concentrations, ultrafine particles, particle number concentrations	Minimal data
Blood pressure	Minimal data
Death	Minimal data
Injuries	No strong mechanistic basis for dependence on indoor environmental quality or EE retrofits
Health care utilization	Although considerable data are available, we decided that this topic is best addressed in a separate paper.
Respiratory infections	Minimal data
Eye symptoms	Minimal data
Skin symptoms	Minimal data
Longstanding illness or disability, e.g., chronic bronchitis	Study periods were considered too short to provide useful data.
Quality of life scores	Expected strong influence by changes in factors other than indoor environmental quality
Pain scores	Minimal data
Sleep	Minimal data

Table S2. Study type categories.

Study type category	Study features*
Randomized controlled trial	“The intervention is delivered to those selected at random to receive the intervention during the study period, this group is the intervention group; those who do not receive the intervention act as a suitable comparison or control group. Key outcomes are assessed before and after delivery of the intervention in both the intervention and the control groups. Changes in the key outcomes are analyzed comparing changes among the intervention group and the control group.”
Prospective controlled study	“The intervention is not randomized. The key outcome is assessed among the study population before and after receipt of the intervention. The change in outcome is compared with the same outcome measurements and changes in a suitable comparison group acting as a control group who have not received the intervention. It is likely that there will be systematic differences in eligibility for the intervention between the intervention and the control group. The key outcome is assessed at the same time points in the intervention and the control group. This design may be referred to as a quasi-experimental design and may also be known as a controlled before and after study (CBA) or a controlled prospective cohort study.”
Prospective controlled study but without statistical use of control group data	This study is like a prospective controlled study; however, the statistical analysis does not compare changes in outcomes in intervention group with changes in outcomes in control group.
Prospective uncontrolled study	“The key outcome is assessed among the study population before and after receipt of the intervention but there is no comparison or control group. This design may also be known as an uncontrolled before and after study or an uncontrolled prospective cohort study.”
Retrospective controlled study	Data are collected after retrofits have been performed, with data collected from a set of retrofit homes and from a similar or matched set of homes that had not been retrofit.
Retrospective uncontrolled study	“This design is similar to a retrospective controlled study but there is no comparison or control group. For the purposes of this review the intervention group will comprise those in receipt of housing improvements that are part of a discrete programme of housing improvement or rehousing delivered at a similar time point.”
Retrospective cross-sectional study	All data are obtained after interventions from a set of homes with and without prior interventions. The associations of the key outcomes with the presence, or absence, of prior interventions is assessed statistically. Matching of home characteristics or multivariate modeling may be employed to control for potential confounding.
Case-crossover study	In this design, each subject serves at their own control. For each subject, health outcome data from a time period with an exposure of interest, e.g. period of high temperatures, are compared to health outcome data for the same subject from a different time period without the exposure of interest.

*Study feature descriptions shown in quotation marks were taken directly from (Thomson, Thomas et al. 2013)

Table S3. Study description compilation.[1]

EE IAQ Health Study
description tablev3.:

Table S4. Study outcome compilation.[1]

EE IAQ Health Study
outcomes tablev3.xl:

Table S5. Excluded papers.

Paper	**Reason not used**
(Alam, Sanjayan et al. 2016)	Paper relies on modeling, it does not present new empirical data, also the outcome is heat related mortality not included as an outcome in our review
(Allen 2005)	Interventions included central heating, bath and shower access, roof/gutter repairs, not EE retrofits
(Arvela, Holmgren et al. 2014)	Review and modeling article that addresses influence of pressure differences and type of mechanical ventilation on indoor radon.
(Bone, Murray et al. 2010)	Review article
(Braubach and Ferrand 2013)	Editorial with brief review, provides no new empirical data
(Breysse, Jacobs et al. 2011)	No pre-retrofit data were collected, changes in health were based on recall by subjects
(Breysse, Dixon et al. 2015)	Residents were relocated from un-renovated to renovated apartments.
(Brugge, Melly et al. 2004)	Renovation measures not limited to EE retrofits
(Budnitz, Berk et al. 1979)	General review with no data on effects of EE
(Camprubi, Malmusi et al. 2016)	Review article
(Carlton, Barton et al. 2019)	Study assessed relationship of home air exchange rates with respiratory symptoms, study does not directly provide information on effects of EE retrofits.

[1] The citations in this table refer to references in the reference list of the main paper file, not to references in the reference list of this supplemental information file.

(Chapman, Howden-Chapman et al. 2009)	Cost benefit analysis using empirical findings of (Howden-Chapman, Matheson et al. 2007)
(Chen and Huang 2012)	Focus is on building design, not EE retrofit
(Colton, MacNaughton et al. 2014)	IAQ of conventional and newly constructed green housing compared, not an assessment of retrofits. Health assessments were associated with moves from conventional to new green homes.
(Critchley, Gilbertson et al. 2007)	Examines why homes remain cold, based on diaries of recorded temperatures, even after EE and heating interventions, does not focus on how EE affects health, the association with temperatures in the diaries with comfort and health are included in Gilbertson et al 2012
(Curl and Kearns 2015, Curl, Kearns et al. 2015)	Study does not separate effects of EE measures from other home improvement measures
(Crump, Macmillan et al. 2009)	Review article
(Davies and Oreszczyn 2012)	Review article
(Dedman, Gunnell et al. 2001)	Study does not address EE retrofits
(Dodson, Udesky et al. 2017)	Provides data on concentrations of volatile organic compounds after renovations, does not indicate how EE renovations affected levels.
(El Ansari and El-Silimy 2008)	Study of how improving warmth affected excess winter deaths, and our review is not including death as an outcome
(Free, Howden-Chapman et al. 2010)	Study of whether improved and non-polluting home heating is associated with reduced school absences; not a study f benefits of EE
(Giancola, Soutullo et al. 2014)	Data obtained from only two apartments
(Gibson, Petticrew et al. 2011)	Synthesis of reviews, not focused on EE
(Hopton and Hunt 1996)	Assessed whether improved home heating to reduce dampness improved health, not a study of EE retrofits
(Howden-Chapman, Viggers et al. 2009)	Review of two prior studies by same research group
(Garland, Steenburgh et al. 2013)	Study involves moving into new homes, studies with moves excluded from our review
(Green, Ormandy et al. 2005)	Not a journal article
(Hamilton, Davies et al. 2011)	Modeled influence of EE interventions on indoor cold temperatures and associated health effects, provides no new empirical data
(Hamilton, Milner et al. 2015)	Modeled effects of EE retrofits in England, provides no new empirical data
(Harrington, Heyman et al. 2005)	This study used survey data to examine attitudes about fuel poverty and warmth, but provides no empirical data on effects of EE retrofits
(Heyman, Harrington et al. 2005)	While paper provides data relating home energy efficiency rating with health, it does not provide data on effects of EE retrofits

(Hood 2005)	Broad discussion of how disparities in built environment influence health, no new data on effects of EE retrofits
(Hopton and Hunt 1996)	Study assessed health consequences of improved heating to reduce dampness and mold, not considered an EE retrofit in this review
(Howden-Chapman, Pierse et al. 2008)	Study of asthma benefits of improved and non-polluting home heating; not a study of benefits of EE retrofits
(Howden-Chapman, Crane et al. 2011)	Review of two prior studies by same research group, provides no new empirical data
(Howden-Chapman and Chapman 2012)	Review article, provides no new empirical data
(Howden-Chapman, Viggers et al. 2012)	Review of two prior studies by same research group and discussion of policy
(Howieson 2018)	Review article, provides no new empirical data
(Jackson, Thornley et al. 2011)	Thermal insulation combined with reduced crowding, ventilation improvements, health and social services assessments and referrals, Did not separate out effects of EE retrofits.
(Jacobs, Kelly et al. 2007)	Review article and discussion of policy, provides no new empirical data
(Jacobs, Kelly et al. 2007)	Focus is new EE homes, not EE retrofits
(Jacobs, Brown et al. 2010)	Review article and not focused on EE interventions
(Jacobs, Ahonen et al. 2015)	Assessed associations of changes in health with moves into new green housing
(Jiránek and Kačmaříková 2014)	Study of a single house
(Kearns, Whitley et al. 2011)	Study assesses health consequences of moving to new homes, not of EE retrofits
(Kuholski, Tohn et al. 2010)	Review and policy discussion that presents no new empirical data.
(Langer and Bekö 2013)	Addresses influence of ventilation rates, but not EE retrofits, on IAQ
(Leech, Raizenne et al. 2004)	Focus is new EE homes, not EE retrofits
(Leivo, Kiviste et al. 2018)	Paper provides analysis of pre-retrofit and post-retrofit values of hydrothermal parameters but does not provide indoor temperature and humidity changes
(Levy, Nishioka et al. 2003)	Modeled health benefits of insulation retrofits and associated reductions in outdoor air pollution, does not provide new empirical data
(Liddell and Morris 2010)	Review article, provides no new empirical data
(Liu, Rohdin et al. 2015)	Compared post retrofit conditions in one multifamily building to conditions in a reference building. However, retrofits included changes in space layout that increased the number of apartments from 19 to 20. And measurements were performed in only two apartments from the

	retrofitted building and one unoccupied apartment from the non-retrofitted building.
(Lloyd, McCormack et al. 2008)	Study provided data on blood pressure, an excluded outcome, and on relied on occupant recall of changes in health since retrofits were completed.
(Lugg and Probert 1997)	Review article, provides no new empirical data
(Maidment, Jones et al. 2014)	Review and meta-analysis, does not provide new primary data; also analysis treats presence of central heating as an energy efficiency measure
(Milne and Boardman 2000)	This is a review article that examines the extent to which energy savings from home energy efficiency improvements in Great Britain are diminished because occupants increase indoor temperatures after EE retrofits are implemented. Provides no new data effects of EE retrofits.
(Milner, Shrubsole et al. 2014)	Modeled how EE retrofits affect radon levels and lung cancer, provides no new empirical data
(Milner and Wilkinson 2017)	Review article
(Meyer 2019)	This study's comparison of energy efficient passive homes to reference homes is not included in the review because the energy efficiency measures were construction features, not the result of EE retrofits
(Milne and Boardman 2000)	Review article
(Mommers, Jongmans-Liedekerken et al. 2005)	Study found association of insulation with reduced respiratory symptoms, but was not a study of EE retrofits.
(Nero 1981)	Study compares radon concentrations in conventional and energy efficient homes but it is not clear that energy efficiency was a consequence of retrofits as opposed to initial construction features. Also three of 17 EE homes were research and demonstration homes and eight used rock beds, potential radon sources, to store heat.
(Norman, Pengelly et al. 1986)	This study examined association of urea formaldehyde foam insulation with respiratory symptoms and lung function. Use of this insulation, not relevant today, is outside of the scope of our review.
(Norton and Brown 2014)	This study does not separately assess the influence of energy efficiency retrofits from other intervention measures.
(Ortiz, Kurvers et al. 2017)	Review article, provides no new empirical data
(Patino and Siegel 2018)	Review article, provides no new empirical data
(Paulin, Diette et al. 2014)	Interventions that aimed to reduce indoor nitrogen dioxide were not EE retrofits

(Peralta, Camprubi et al. 2017)	Study outcome was mortality, which is an excluded outcome.
(Peretti, Pasut et al. 2015)	Assessed effect of adding mechanical ventilation to an EE retrofit , did not assess effects of EE retrofits
(Platt, Mitchell et al. 2007)	This study assessed effects of adding central heating, not energy efficiency retrofits. Also, the document is not a journal article.
(Pressyanov, Dimitrov et al. 2015)	Paper addresses a novel measurement method to analyze radon level in buildings with EE retrofits
(Preval, Chapman et al. 2010)	Study of health benefits of improved and non-polluting home heating; not a study f benefits of EE
(Richardson and Eick 2006)	A review / discussion of issues.
(Ringer 2014)	Paper addresses effects of EE construction features, not EE retrofits, on indoor radon
(Roulet, Johner et al. 2006)	Paper relates building energy performance with perceived outcomes, but paper is not an assessment of EE retrofits
(Sandel, Phelan et al. 2004)	Study focuses on lead abatement interventions not on EE retrofits
(Schenker, Weiss et al. 1982)	This study assessed health of residents of homes with urea formaldehyde foam insulation. Use of this insulation, not relevant today, is outside of the scope of our review.
(Schweitzer and Tonn 2003)	Review article, provides no new empirical data
(Sharpe, Thornton et al. 2015)	This paper reports on an association of asthma outcomes with home energy efficiency ratings but does not specifically address associations of asthma with EE retrofits
(Sharpe, Machray et al. 2019)	This ecological study employed aggregated data for geographic regions of England, not data at the individual home level
(Shrestha, Humphrey et al. 2019)	Paper assesses the correlation of an estimated annual average ventilation rate with visual evidence of IEQ problems and with perceived IAQ, does not directly assess effects of EE retrofits
(Shrubsole, Ridley et al. 2012)	Provides model predictions, not empirical data
(Shrubsole, Macmillan et al. 2014)	Review article, provides no new empirical data
(Shrubsole, Hamilton et al. 2019)	Review article, provides no new empirical data
(Somerville, Mackenzie et al. 2000)	Intervention was installation of central heating, not considered an EE measure in this review
(Takaro, Krieger et al. 2011)	Assesses effect of moving into new asthma friendly home, studies with moves excluded from our review
(Thomson, Petticrew et al. 2001)	Review article, provides no new empirical data
(Thomson, Thomas et al. 2013)	Review article, provides no new empirical data
(Thomson, Thomas et al. 2009)	Review article, provides no new empirical data

(Thomson, Morrison et al. 2007)	Study of health consequences of moves to new housing, moves excluded from our review
(Thomson and Petticrew 2007)	Editorial, provides no new data
(Thomson and Thomas 2015)	Provides review and theories about how housing interventions affect health, no new empirical data on EE retrofits
(Vandentorren, Bretin et al. 2006)	Study relates lack of insulation to death during heat wave but does not focus on EE retrofits
(Viegi, Paoletti et al. 1991)	Study assesses health consequences of type of heating, but does not assess effects of EE retrofits
(Walker, Mitchell et al. 2009)	Intervention was installation of central heating, not considered an EE measure in this review
(Walker, Mitchell et al. 2005)	Assessed whether extent and duration of domestic heating influenced health, not a study of EE retrofits
(Wang, Kuckelkorn et al. 2017)	Reviews energy and IEQ performance of homes built to passive house standard, does not specifically address EE retrofits
(Wells, Berges et al. 2015)	Paper compares two levels of EE retrofits, does not assess effects of EEF retrofit versus no retrofit
(Wierzbicka, Pedersen et al. 2018)	Includes brief review of linkage of EE to IEQ, but provides no new empirical data
(Wilkinson, Armstrong et al. 2005)	Conference abstract, provides no detailed data
(Wilkinson, Smith et al. 2007)	Review article, provides no new empirical data
(Wilkinson, Smith et al. 2009)	Review / model predictions, does not provide new empirical data
(Willand, Ridley et al. 2015)	Review article, provides no new empirical data
(Woodfine, Neal et al. 2011)	Assesses benefits to those with asthma of adding ventilation and central heat, not EE retrofits
(Yu and Kim 2012)	Review article, does not address EE retrofits

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